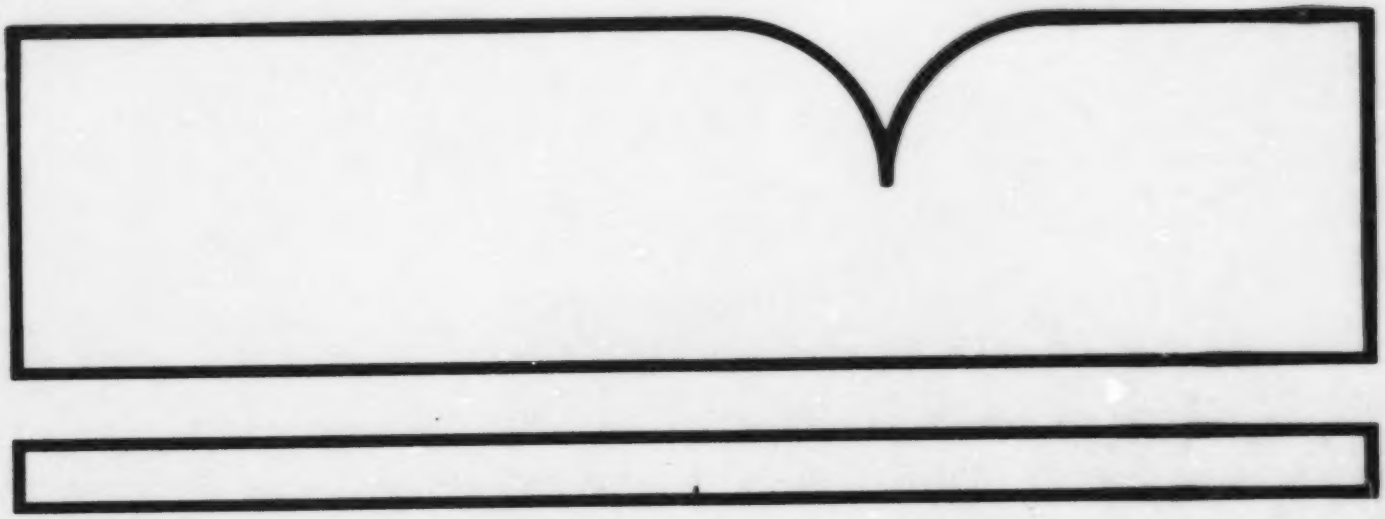
PB81-111858

Thermal Analysis of the Manning S-4000 Portable Wastewater Sampler

Environmental Monitoring and Support Lab.-Cincinnati, OH

Oct 80



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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/4-80-045	2.
3. RECIPIENT'S ACCESSION NO. PB81 111858	
4. TITLE AND SUBTITLE THERMAL ANALYSIS OF THE MANNING S-4000 PORTABLE WASTEWATER SAMPLER	5. REPORT DATE October 1980 Issuing Date.
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Philip C. L. Lin	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Monitoring and Support Laboratory - Cinti. Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same as above	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA-600/06
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

This study investigated the feasibility of mathematically designing a portable sampler with an ice compartment for the preservation of samples collected in sequence automatically at about 4°C for a 24-hour period under certain environmental conditions, specifically 35°C for both the ambient temperature and the samples.

A Manning S-4000 sampler was selected in this study. A mathematical model to simulate the sample cooling process was developed and experimental measurements on the sampler cooling system were also conducted.

The experimental results indicated that about 80 to 96 percent of the cooling capacity of the sampler was lost to the surroundings after an exposure of 18 to 24 hours at a temperature ranging from 23.5 to 33°C for the environment and the initial samples.

A modified cooling system is suggested in this report. The new system has a cooling capacity to lower 24 500-ml samples to about 4°C at a cycle time of 1 hour and a temperature of 35°C for both the surroundings and the initial samples over a 24-hour period.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sampling, Samplers, Automatic samplers, Mathematical model, Sample cooling	68D	14B

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 44
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

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EPA 600/4-80-045
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THERMAL ANALYSIS OF THE MANNING S-4000 PORTABLE WASTEWATER SAMPLER

by

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FOREWORD

Environmental measurements are required to determine the quality of ambient waters and the character of waste effluents. The Environmental Monitoring and Support Laboratory - Cincinnati conducts research to:

Develop and evaluate techniques to measure the presence and concentration of physical, chemical, and radiological pollutants in water, wastewater, bottom sediments, and solid waste.

Investigate methods for the concentration, recovery, and identification of viruses, bacteria, and other microbiological organisms in water. Conduct studies to determine the responses of aquatic organisms to water quality.

Conduct an Agency-wide quality assurance program to assure standardization and quality control of systems for monitoring water and wastewater.

The Instrumentation Development Branch of the Environmental Monitoring and Support Laboratory provides functional designs relating to water quality instrumentation systems. This report which investigates heat transfer characteristics of an automatic wastewater sampler, provides a mathematical model with which manufacturers can design an ice-cooled portable sampler capable of preserving samples under an extreme temperature, 35°C, for both the environment and the samples.

Robert L. Booth
Acting Director
Environmental Monitoring and Support Laboratory
Cincinnati

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ABSTRACT

This study investigated the feasibility of mathematically designing a portable sampler with an ice compartment for the preservation of samples collected in sequence automatically at about 4°C for a 24-hour period under certain environmental conditions, specifically 35°C for both the ambient temperature and the samples.

A Manning S-4000 sampler was selected in this study. A mathematical model to simulate the sample cooling process was developed and experimental measurements on the sampler cooling system were also conducted.

Comparisons between the model and the tests indicated that the accuracy of the mathematical model was mainly within 3°C. Phase differences between sample temperature histories for each corresponding sample were minimal.

The sampler has a cooling space of 4.2 kg of ice. However, only about half of the cooling space can be packed with cube ice unless the container is filled with water and placed in a freezer. In the tests, about 50 percent of the cooling space was filled with ice and the other 50 percent was filled with water. The experimental results indicated that a large amount of heat from the environment to the sampler was found in the tests. About 80 to 96 percent of the cooling capacity of the sampler was lost to the surroundings. After an exposure of 18 to 24 hours at a temperature ranging from 23.5 to 33°C for the environment and the initial samples, the final lowest temperatures of the samples were only 0.5 to 3°C less than the respective ambient temperature. The time required for a sample to reach its lowest temperature is 4 to 6 hours, indicating that the sampler insulation is insufficient and the sample cooling rate is too slow.

A modified cooling system is suggested in this report. The new system has a cooling capacity to lower 24 500-ml samples to about 4°C at a cycle time of 1 hour and a temperature of 35°C for both the surroundings and the initial samples over a 24-hour period.

It is concluded that mathematical models for the development of specifications for a sampler cooling system are possible.

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SYMBOLS

A	Contact area between the coolant and the sampler bottom, 613 cm^2 (0.66 ft^2).
A_b	Contact area between the bottle and the sampler bottom, 38.7 cm^2 (6/144 ft^2).
$A_{f,i}$	Contact area between bottle i and the coolant, 32.26 cm^2 (5/144 ft^2).
$A_{i+1,i}$, $A_{i-1,i}$	Contact area between bottles i and i+1, and between bottles i and i-1, respectively, 129 cm^2 (20/144 ft^2).
$C_{f,i}$	Thermal conductance between sample i and the coolant, cal/hr-cm^2-^oC.
$C_{i+1,i}$, $C_{i-1,i}$	Thermal conductance between samples i and i+1, and between samples i and i-1, respectively, cal/hr-cm^2-^oC.
C_p	Specific heat of water, 1 cal/gm-^oC.
dx	Thickness of the bottle, 1.25 mm.
g	Gravitational acceleration, 980 cm/sec^2.
G	Solar irradiation at the earth orbit, 0.476 cal/hr-cm^2 (442 Btu/hr-ft^2).
h	Surface film coefficient, cal/hr-cm^2-^oC.
$h_{f,i}$	Surface film coefficient between sample i and the coolant, cal/hr-cm^2-^oC.
h_i	Surface film coefficient between sample i and the sampler wall, cal/hr-cm^2-^oC.
$h_{i+1,i}$, $h_{i-1,i}$	Surface film coefficient between samples i and i+1, and between samples i and i-1, respectively, cal/hr-cm^2-^oC.
h_{ice}	Surface film coefficient between the water coolant and the ice, cal/hr-cm^2-^oC.
h_o	Surface film coefficient between the environment and the sampler, cal/hr-cm^2-^oC.

j	j the iteration.
j+1	j+1 th iteration.
K	Thermal conductivity of the sampler wall, 2.23 cal/hr-cm-^{o}C (0.15 Btu/hr-ft-^{o}F).
K_a	Thermal conductivity of air, 0.22 cal/hr-cm-^{o}C (0.015 Btu/hr-ft-^{o}F).
K_b	Thermal conductivity of the bottle, 3.72 cal/hr-cm-^{o}C (0.25 Btu/hr-ft-^{o}F).
kk	Number of bottles filled with water.
K_w	Thermal conductivity of water, 5.21 cal/hr-cm-^{o}C (0.35 Btu/hr-ft-^{o}F).
l	Bottle height, 12.7 cm (5 in.).
m	Sample mass, gm.
M	Water mass in the coolant, gm.
n	Number of time steps.
N	Total number of bottles in the sampler, 24.
Q_i	Heat gain through the sampler wall to sample i, cal/hr.
Q_{ice}	Heat gain (negative) from the solid ice to the coolant water, cal/hr.
R_i	Inside radius of the sampler, 21.59 cm (8.25 in.).
R_{ice}	Radius of the ice (assume that the ice is a cylindrical body with a height of bottle length), cm.
R_o	Outside radius of the sampler, 22.23 cm (8.75 in.).
t	Time, hr.
T_i, T_{i+1}, T_{i-1}	Temperature in samples i, i+1, i-1, respectively, ^{o}C.
T_f	Temperature in the water coolant, ^{o}C.
T_{fo}	Ice temperature, 0^{o}C.
T_m	Mean surface temperature, ^{o}C.
T_o	Ambient temperature, ^{o}C.
w	Relaxation factor, 1.5.
Δt	Time increment, 1/60 hr.
Δx	Thickness of the sampler bottom, 1.27 cm (0.5 in.).
Δx_{wi}	Air gap between the sampler wall and the bottle, 3.5 mm.
ΔT	Half of the temperature difference between two fluids, ^{o}C.

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σ	Stefan-Boltzmann constant. 0.488×10^{-8} cal/hr-cm^2-$^oK^4$ (0.1714×10^{-8} Btu/hr-ft^2-$^oR^4$).
ε	Infrared emissivity of the surface.
α	Solar absorptivity of the surface.
γ	Angle between the sun rays and the surface normal.
N_{nu}	Nusselt number.
N_{pr}	Prandtl number, $\mu C_p/K_w$, or 13.37-0.2556 Tm for water.
N_{gr}	Grashof number $l^3 \rho^2 g \beta \Delta T / \mu$.
ρ	Density of water, 1 gm/cm^3.
β	Thermal expansion coefficient, $(8.379 Tm + 54) \times 10^{-6}/^oC$ for water.
μ	Viscosity, 64.35-0.57 Tm gm/cm-hr for water.
C, a	Constants.

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SECTION 1

INTRODUCTION

A wastewater sample, regardless of its nature--domestic sewage, or industrial or natural waste--generally deteriorates after acquisition. This is due to chemical and biological changes in the sample. To obtain a complete representative sample, therefore, requires a perfect preservation technique. Currently such a method is unavailable.

Preservation methods now in use are meant to retard the biological action and hydrolysis of chemical compounds and complexes, and to reduce the loss of volatile constituents. Techniques utilized employ pH control, use of chemical additives, refrigeration, or freezing. Refrigeration at a temperature near freezing is the best preservation technique, although not all types of samples are applicable to it. A variety of samples should be preserved at 4°C. This is the case with samples associated with acidity, alkalinity, biological oxygen demand (BOD), bromide, color, cyanides, fluoride, hardness, iodide, ammonia, nitrate, nitrite, oil and grease, organic carbon, pH, phenolics, phosphorus, residue, silica, specific conductance, sulfate, turbidity, and odor, among others. Most of the samples except BOD and pH (holding time - 6 hours at 4°C) can be kept up to 24 hours at 4°C. Some can even be preserved up to 7 days at 4°C. Readers are referred to Reference 1 for more detailed information.

Many types of sampling equipment used to collect grab, continuous or sequential samples are available on the market. A separate compendium of commercially available sampling equipment with descriptions and characterizations was prepared by Shelley and Kirkpatrick[2] and Lauch[3] respectively. Some of the devices are equipped with ice compartments or refrigeration systems. Because of the importance of low temperature sample preservation, Lauch[4,5] conducted experimental studies on two portable sampler cooling systems. Although the amount of ice used was not indicated in his tests, none of the tested samplers was capable of preserving a sample at 4°C under normal operating conditions for a 24-hour period. Moreover, none of the sampler manufacturers specifically addressed the thermal characteristics of the samplers.

The purpose of this study is to develop a mathematical model for predicting the sample cooling process in a sampler and therefore to facilitate the experimental evaluation of the sampler cooling system. It is evident that extension of this approach to specification guidelines for a sampler cooling system design is of greater importance, presuming that it is inadequate and/or not fast enough to cool a sample to 4°C under various environmental conditions.

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A widely-used Manning S-4000 sequential sampler with an ice compartment was selected in this study. A mathematical model was developed to simulate its cooling system. The Crank-Nicolson implicit numerical technique was used to solve the equation set. Computations were then carried out with a computer simulation program in Fortran IV by the Environmental Protection Agency (EPA) PDP11/70 computer. A laboratory study to confirm the accuracy of the model as the basis for developing a cooling system design guideline in a sampler was also conducted. Results from both experimental measurements and calculations were plotted for comparisons.

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SECTION 2

CONCLUSIONS

The sampler cooling capacity is inadequate for sample preservation by icing under the testing conditions. Final sample temperatures in the tests after 18 or 24 hours were about 0.5 to 3°C less than the respective ambient temperature ranging from 23.5 to 33°C. It is clear that sample preservation by icing is impossible using this sampler. Furthermore, the sample cooling rate was slow, requiring about 4 to 6 hours for a sample to reach its minimum temperature.

As for the accuracy of the mathematical model, it was found that the maximum temperature difference for any sample between experimental and theoretical results was within 3°C. Exceptions did result from improperly installed thermocouples in three sample bottles in two tests. Each sample had a similar trend of temperature history with respect to time.

The simulation program developed for the sampler cooling system is generalized. The applications are as follows:

- The mathematical model can provide a guideline for the design of a sample cooling system and will minimize experimental work and manpower in evaluating sampler cooling capacity.

- The computer program can be applied to different combinations of sampler material, bottle thickness, number of bottles, number of samples, ice mass, sample mass, cycle time, duration time and so on, provided the sampler geometry is similar.

- Temperature-time histories of samples can be calculated and plotted directly from the computer program under various conditions.

- Experimental data of sample temperature can be fed into the computer program for plotting.

- Heat transfer from outside the sampler can be calculated for any length of time, thus enabling the required total coolant space to be predicted.

- Development of specifications based on the model for the product design is possible.

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Study of the effect of the solar radiation on the sampler casing indicated that certain materials, such as white epoxy paint with a low solar absorptivity and a high infrared emissivity, can minimize or even eliminate the solar effect on the heat gain through the sampler wall.

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SECTION 3

RECOMMENDATIONS

Since the Manning S-4000 sampler cooling system is not acceptable under the test conditions, the following recommendations are suggested to improve its performance:

- Increase the sampler insulation.
- Increase the sampler cooling space.
- Increase the contact area between the coolant and the bottle.
- Increase ice capacity by placing the container in a freezer.

Based on the mathematical model and the recommendations above, a prototype design of a new cooling system in the Manning sampler is suggested. In the prototype, the sampler wall is 5 cm (2 in.) thick. The coolant space is large enough to hold 14 kg of ice. The contact area is increased to 130 cm^2 (0.14 ft^2) and the thermal conductivity of the wall is less than 0.45 cal/hr-cm-^oC (0.03 Btu/hr-ft-^oF). This design is capable of preserving 24 500-ml samples in this sampler at 4^oC for a 24-hour period under certain environmental conditions (35^oC for both samples and the environment).

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SECTION 4

DESCRIPTION OF SAMPLER

The Manning S-4000 automatic, sequential sampler as shown in Figure 1 is a pressure-vacuum type sampler. It contains 24 bottles made of polypropylene, each of which has a capacity of 500 ml. The bottle container is made of structurally-foamed plastic to prevent heat transfer from the surroundings to the sample when ice is stored in the sampler for sample preservation.

The sampling process is activated by a 12-volt battery. Sampling cycles may be initiated from an internal timer, an external contact closure, or a manual push button. Twenty-four discrete bottles can be filled at intervals of 15 minutes to 24 hours. Also, it is possible to fill from 1 to 4 consecutive bottles and allow each discrete bottle to be composed of 1 to 5 samples.

The manufacturer's schematic diagram shown in Figure 2 illustrates how the sampler functions. The sequence of sampler operation is as follows:

1. The internal quartz crystal-controlled timer in the sampler initiates the sampling cycle control.

2. The compressor pressurizes the measuring chamber and purges the intake line. The solenoid valve then inverts the compressor lines to create a vacuum in the measuring chamber and a sample is sucked into the chamber.

3. The electronic level sensor in the measuring chamber controls the solenoid valve position so that the excess sample is forced out of the intake lines.

4. The pinch valve then opens, and the measured amount of sample is forced into the sample bottle.

5. The pinch valve closes and the compressed air purges the intake line.

6. The compressor shuts off and the spout steps to the next bottle.

7. This completes a cycle. This process continues until the 24th bottle is filled with a sample, at which time the sampler automatically shuts off.

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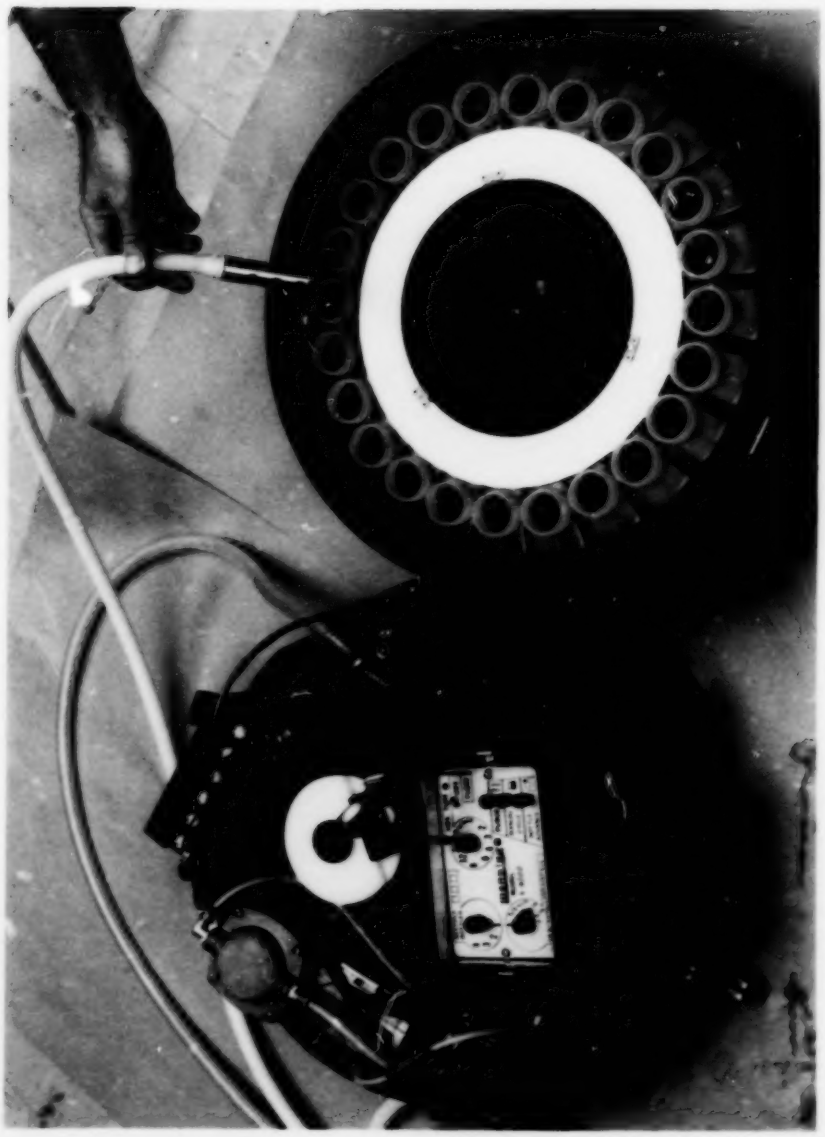

Figure 1. Photograph of sampler.

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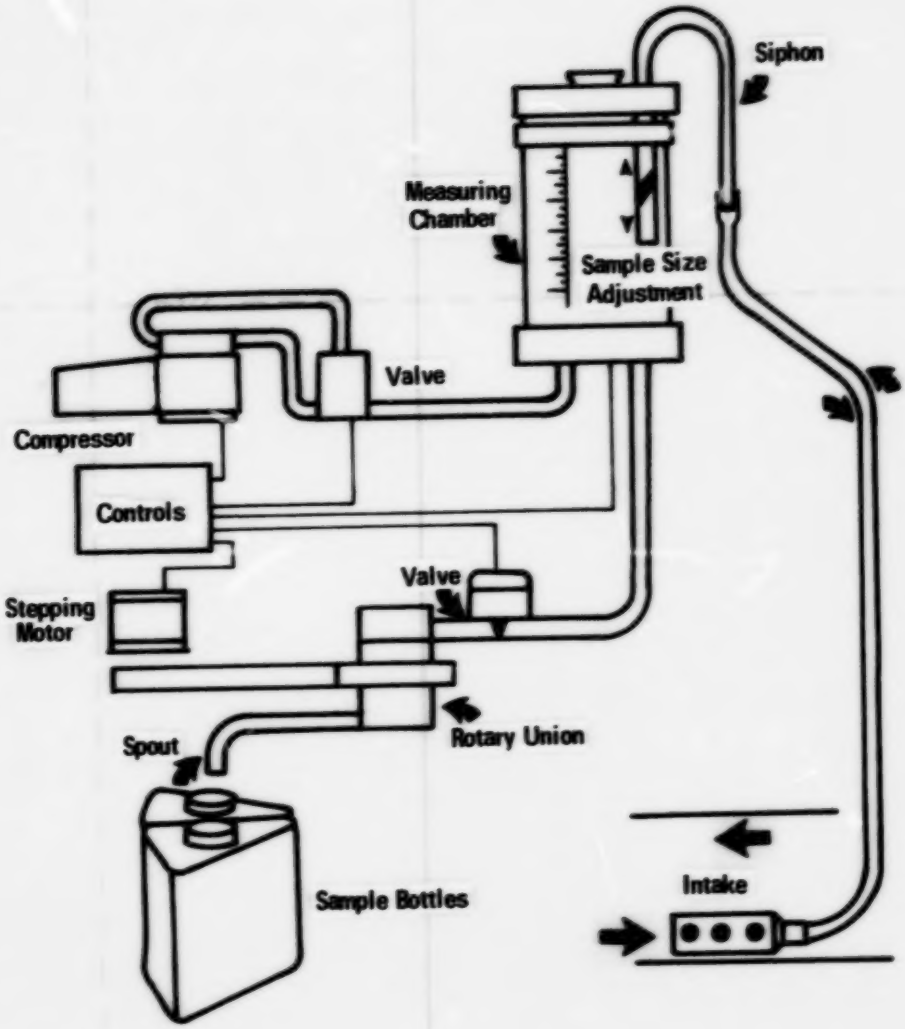

Figure 2. Schematic diagram of sampler function.

SECTION 5

DEVELOPMENT OF MATHEMATICAL MODEL OF SAMPLER COOLING SYSTEM

Thermal analysis of the sampler cooling system is complicated by the shape and arrangement of bottles in the sampler, the amount of coolant, temperature, solar radiation, etc. Hence, to accurately predict a sample temperature history is extremely difficult. A closed-form solution for the cooling system is clearly impossible. However, a numerical solution is generally possible.

Heat transfer mechanisms associated with the sampler generally consist of conduction, convection, and radiation. Radiation comes mainly from the solar irradiation of the sampler casing. Its effect on the casing can be eliminated or minimized by properly choosing a material with properties of a low solar absorptivity and yet a high infrared emissivity. Conduction and convection are the dominant factors in reducing the sample temperature in a sampler. In this study, all three phases of heat transfer--conduction, convection, and radiation--are investigated.

HEAT TRANSFER BY CONDUCTION AND CONVECTION IN THE SAMPLER

The simulation of the thermal characteristic of the sampler is greatly simplified by the following assumptions:

- Transient response of samples with negligible internal resistance to the heat is assumed.
- Heat transfer in the sample occurs only in the r- and θ-directions.
- No heat transfer exists between empty bottles.
- Heat transfer to the coolant comes from the samples in the r-direction and from the top and bottom of the sampler in the axial direction.

Two sets of heat transfer equations were then derived. Symbols utilized in the equations are listed in the Symbols section. The two sets of equations are (with bottles numbered as shown in Figure 3):

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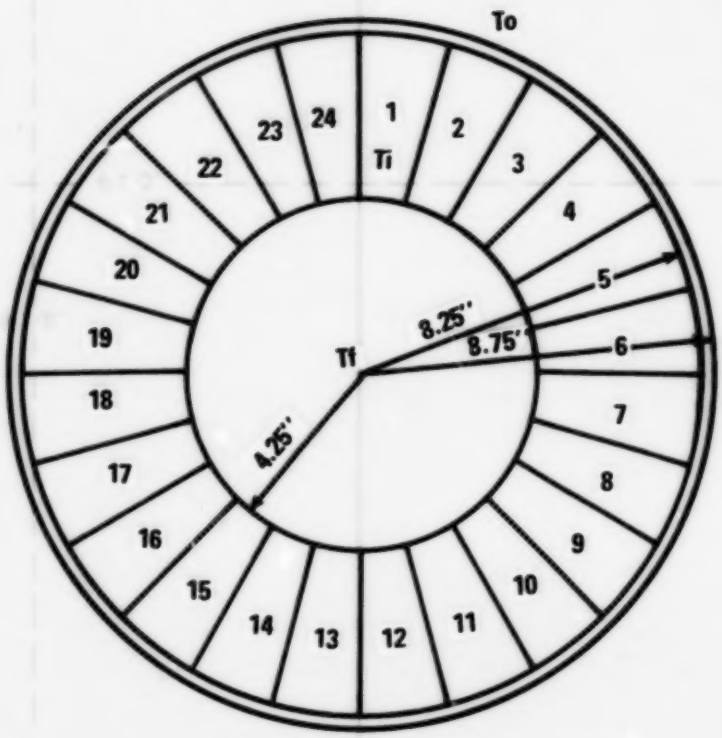

Figure 3. Top view of sample container.

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i. Heat transfer Equation for Sample i

$$mC_p \frac{dT_i}{dt} = C_{i+1,i}\, A_{i+1,i}(T_{i+1} - T_i) + C_{f,i}\, A_{f,i}(T_f - T_i)$$

$$+ C_{i-1,i}\, A_{i-1,i}(T_{i-1} - T_i) + Q_i \qquad (5\text{-}1)$$

in which

i = sample number 1,2,.....,24.

Equation (5-1) gives the transient temperature response of sample i. The first, second, and third terms represent heat gain of sample i from sample i+1, the water coolant, and sample i-1, respectively. The last term is the heat gain from the environment to sample i.

By introducing

$$\tau_{i+1,i} = \frac{C_{i+1,i}\, A_{i+1,i}}{mC_p}$$

$$\tau_{i-1,i} = \frac{C_{i-1,i}\, A_{i-1,i}}{mC_p}$$

$$\tau_{f,i} = \frac{C_{f,i}\, A_{f,i}}{mC_p} \qquad (5\text{-}2)$$

Equation (5-1) may be written as follows:

$$\frac{dT_i}{dt} = \tau_{i+1,i}(T_{i+1} - T_i) + \tau_{f,i}(T_f - T_i) + \tau_{i-1,i}(T_{i-1} - T_i)$$

$$+ \frac{Q_i}{mC_p} \qquad (5\text{-}3)$$

ii. Heat Transfer Equation for the Water Coolant

$$MC_p \frac{dT_f}{dt} = \sum_{i=1,2}^{kk} C_{f,i}\, A_{f,i}(T_i - T_f) + \frac{2A}{\frac{\Delta x}{K} + \frac{1}{h_o}}(T_o - T_f)$$

$$+ Q_{ice} \qquad (5\text{-}4)$$

This equation gives the transient response of the temperature of the water coolant. The first and second terms represent heat gain from samples and the surroundings to the coolant, respectively. The last term is the heat gain from ice to the water coolant. By similar transformations as in i, equation (5-4) becomes:

$$\frac{dT_f}{dt} = \sum_{i=1,2}^{kk} \tau_{f,i}(T_i - T_f)\frac{m}{M} + \frac{2A}{(\frac{\Delta x}{K} + \frac{1}{h_o})MC_p}(T_o - T_f)$$

$$+ \frac{Q_{ice}}{MC_p} \qquad (5\text{-}5)$$

Equations (5-3) and (5-5) may be transformed into finite difference forms and solved simultaneously for T_i and T_f in terms of time, t, with the boundary and initial conditions provided.

SOLAR IRRADIATION ON A SAMPLER

A heat rejection surface in the solar environment should have a low value of solar absorptivity, α, and a high value of infrared emissivity, ε, since the surface radiates mainly in the infrared band. The following equation represents the equilibrium temperature of a surface under the sun provided there is no other heat transfer mechanism involved:

$$\sigma\varepsilon T_{eq}^4 = \alpha\, G \cos\gamma \qquad (5\text{-}6)$$

Equation (5-6) may be rewritten as:

$$T_{eq} = [\frac{\alpha}{\varepsilon}\frac{G\cos(\gamma)}{\sigma}]^{1/4} \qquad (5\text{-}7)$$

It is clear that a decrease of α/ε will reduce the surface equilibrium temperature. Examples given below illustrate the importance of the choice of a sampler surface in order to obtain a low equilibrium temperature.

Example 1

A solar collector material - 410 stainless steel

$\alpha = 0.764$
$\varepsilon = 0.180$
$\gamma = 45$ degrees

Thus,

$T_{eq} = 938^oR$ (or 248^oC)

Example 2

A heat rejection material - aluminum coated with white epoxy paint

$\alpha = 0.248$
$\varepsilon = 0.882$
$\gamma = 45$ degrees

Thus,

$$T_{eq} = 476^{o}R \text{ (or } -9^{o}C)$$

Therefore, a low value of α/ε for a sampler casing can minimize or eliminate the solar effect on the heat gain of a sampler. For more detailed information on this subject, readers are referred to Reference 6.

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SECTION 6

NUMERICAL ANALYSIS OF MATHEMATICAL MODEL

NUMERICAL TECHNIQUE

Numerical solutions were obtained by transforming the mathematical expressions, (5-3) and (5-5) into the Crank-Nicolson finite difference forms:[7]

$$T_i^{j+1} = T_i^j + w\,[a_2^n(\tau_{f,i}^n\, T_f^j + \sum_{\substack{k=i-1 \\ k\neq i}}^{k=i+1} \tau_{k,i}^n\, T_k^j + a_1^n) - T_i^j] \qquad (6\text{-}1)$$

where

$$a_1 = \frac{2}{\Delta t}\, T_i + \tau_{f,i}(T_f - T_i) + \sum_{\substack{k=i-1 \\ k\neq i}}^{k=i+1} \tau_{k,i}(T_k - T_i) + \frac{2\,Q_i}{mC_p}$$

$$a_2 = \frac{\Delta t}{2} \Big/ \left[1 + \frac{\Delta t}{2}\left(\tau_{f,i} + \sum_{\substack{k=i-1 \\ k\neq i}}^{k=i+1} \tau_{k,i}\right)\right]$$

$$T_f^{j+1} = T_f^j + w\,[b_2^n(\frac{m}{M} \sum_{i=1,2}^{kk} \tau_{f,i}^n\, T_i^j + b_1^n) - T_f^j] \qquad (6\text{-}2)$$

where

$$b_1 = \frac{m}{M} \sum_{i=1,2}^{kk} \tau_{f,i}(T_i - T_f) + \frac{4A}{(\frac{\Delta x}{K} + \frac{1}{h_o})MC_p}(T_o - T_f) + \frac{2\,Q_{ice}}{MC_p}$$

$$+ \frac{2\,T_f}{\Delta t}$$

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$$b_2 = \frac{\Delta t}{2} / \left[1 + \frac{\Delta t}{2}\left(\frac{m}{M} \sum_{i=1,2}^{kk} \tau_{f,i}\right)\right]$$

Equations (6-1) and (6-2) were solved simultaneously for T_i and T_f for the n+1 th time step by a successive overrelaxation technique.[7] The same procedure was repeated for solutions of the successive time steps until all bottles were filled with a sample or until the specified duration time was reached. Equations (6-1) and (6-2) cannot, however, be solved without the boundary and initial conditions provided.

BOUNDARY AND INITIAL CONDITIONS

Boundary and initial conditions for equations (6-1) and (6-2) are partially given in Figure 3. The numbered bottles were filled with samples in the increasing sequence. The following are also required for solving equations (6-1) and (6-2).

Heat transfer, Q_i, through the sampler wall to sample i is

$$Q_i = \left[\frac{2\pi l}{\frac{\ln\frac{R_o}{R_i}}{K} + \frac{\ln\frac{R_i}{R_i - \Delta x_{wi}}}{K_a} + \frac{1}{R_i h_i} + \frac{1}{R_o h_o}}\right) NmC_p + \frac{A_b}{\left(\frac{\Delta x}{K} + \frac{1}{h_o}\right)mC_p}\Big](T_o - T_i) \qquad (6\text{-}3)$$

Heat transfer, Q_{ice}, from the solid ice to the water coolant is

$$Q_{ice} = 2\pi R_{ice}\, l\, h_{ice}\, (T_{fo} - T_f) \qquad (6\text{-}4)$$

Coefficients $\tau_{f,i}$, $\tau_{i+1,j}$, and $\tau_{i-1,i}$ in equations (6-1) and (6-2) have to be determined for the n'th time-step before these equations can be solved for the n+1 th time-step. These coefficients were defined in equation (5-2) in the previous section. They are

$$\tau_{f,i} = \frac{C_{f,i}\, A_{f,i}}{mC_p}$$

$$\tau_{i+1} = \frac{C_{i+1,i}\, A_{i+1,i}}{mC_p}$$

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$$\tau_{i-1,i} = \frac{C_{i-1,i} A_{i-1,i}}{mC_p}$$

and $C_{f,i}$, $C_{i+1,i}$, and $C_{i-1,i}$ are defined as

$$C_{f,i} = \frac{1}{\frac{2}{h_{f,i}} + \frac{dx}{K_b}}$$

$$C_{i+1,i} = \frac{1}{\frac{2}{h_{i+1,i}} + \frac{2\,dx}{K_b}} \qquad (6\text{-}5)$$

$$C_{i-1,i} = \frac{1}{\frac{2}{h_{i-1,i}} + \frac{2\,dx}{K_b}}$$

All parameters in equations (6-1) and (6-5) were specified except surface film coefficients which were calculated. A surface film coefficient was calculated by introducing a dimensionless heat transfer coefficient:

$$N_{nu} = \frac{hl}{K_w} \qquad (6\text{-}6)$$

in which

N_{nu} = Nusselt number

Nusselt number was found to obey the following relationship:

$$N_{nu} = C(N_{pr}\, N_{gr})^a \qquad (6\text{-}7)$$

in which

C, a = constants.

N_{pr} = Prandtl number.

N_{gr} = Grashof number.

Nusselt number for a vertical sample bottle was approximated by that of a vertical plate. Values for a and C for a vertical plate (in free convection) are listed by Chapman. Figure 4 shows the experimental relationship

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between N_{nu} and $N_{gr}N_{pr}$. According to Chapman, the following approximations are used for a vertical plate:

$$10^{-1} < N_{gr}\,N_{pr} \leq 10^{4} \quad : \text{use Figure 4}$$

$$10^{4} < N_{gr}\,N_{pr} \leq 10^{9} \quad : C = 0.59, \quad a = \frac{1}{4}$$

$$10^{9} < N_{gr}\,N_{pr} \leq 10^{12} \quad : C = 0.129, \quad a = \frac{1}{3} \qquad (6\text{-}8)$$

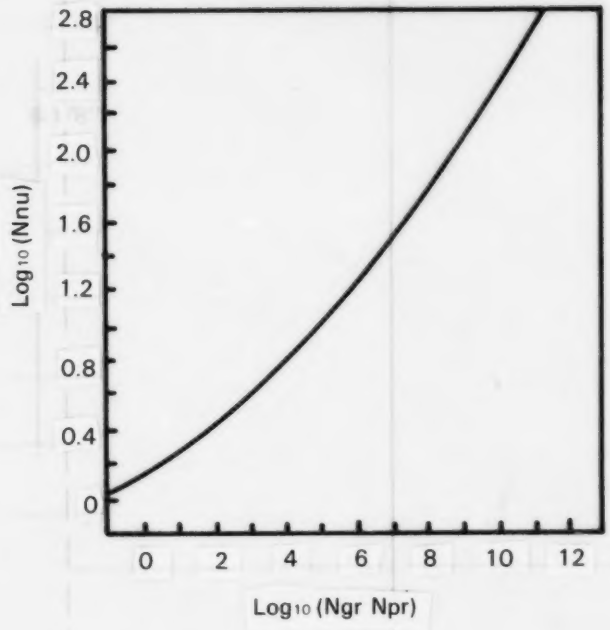

Figure 4. Recommended correlation for free convection around vertical plane surfaces (Reference 6).

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SECTION 7

TESTING EQUIPMENT AND TEST PROCEDURES

A laboratory study to confirm the mathematical model on the Manning sampler cooling system was conducted. The laboratory facilities included:

- Environmental chamber, Zero-Temp Inc.
- Electronik 16 recorder, Honeywell Industrial Division.
- Bath and circulator, Forma Scientific, Inc.
- Matheson thermometer, -1 to 51°C, 1/10 division.

A thermocouple was placed centrally in each of the 24 bottles in the sampler and the wires were firmly taped to the sampler casing. The sampler was then placed in the environmental chamber. The other ends of the thermocouples were passed through a hole of the chamber and connected to the Honeywell Electronik 16 recorder. The recorder would take 24 discrete temperature readings at intervals of 6 seconds at a recording speed of 1 to 8 in./hr. It was difficult to distinguish 24 discrete temperature readings on the recorder at 8 in./hr so that only about 10 randomly selected thermocouples were connected to the recorder for each test. The accuracy of the recorder was about ±0.5°C in the testing range of 0 to 40°C. The bath and circulator filled with water samples was then placed in the chamber.

Test procedures for each run were as follows:

1. Turned on the bath and circulator and set temperature controller to the desired temperature of the water sample to be taken.

2. Turned on the environmental chamber and set its dry bulb temperature to the desired ambient temperature.

3. Used a Matheson thermometer to check the temperature of the bath and circulator after it reached a steady state.

4. After the chamber reached a steady state, placed weighted ice and water into the sampler ice compartment. Measured initial water temperature.

5. Turned on the recorder.

6. Set the sampler cycle time and started to collect the first sample from the bath and circulator.

7. Stopped this run after the duration time was reached or total number of samples was taken.

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SECTION 8

RESULTS AND DISCUSSION

In this study, the thermal conductivity of the bottle made of high density polypropylene was assumed to be 3.72 cal/hr-cm-^{o}C (0.25 Btu/hr-ft-^{o}F); and that of the sampler wall made of structurally-formed plastic was 2.23 cal/hr-cm-^{o}C (0.15 Btu/hr-ft-^{o}F) (values estimated from Reference 8 and 9).

This study included five tests under various conditions for comparisons with corresponding theoretical calculations on the Manning S-4000 sampler cooling system; three calculations were made with the modified sampler.

EXPERIMENTAL AND THEORETICAL RESULTS

Accuracy of the computer program was verified by comparing the energy balanced sample equilibrium temperature in the sampler without heat gain from the surroundings with that obtained by numerical solution of equations (6-1) and (6-2), setting the thermal conductivity of the sampler wall equal to zero and the surface film coefficient of the bottle equal to 2976 cal/hr-cm^{2}-^{o}C (200 Btu/hr-ft^{2}-^{o}F).

Data such as ambient temperature, sample volume, ice mass, etc. for the accuracy test are shown in Figure 5. About 1 hour was required for sample 1 to drop its temperature from 30 to 0.35^{o}C. The final temperature of all samples was about 10.31^{o}C after 24 hours. By comparing the energy balanced temperature, 10.08^{o}C with 10.31^{o}C, the program was considered sufficiently accurate for the present purpose.

The experimental results and theoretical calculations are compared in plots 6 to 10. Dashed lines in all plots represent results from experiments; the solid lines represent those theoretically calculated. Detailed testing conditions are summarized in Table 1.

TABLE 1. TESTING DATA ON MANNING SAMPLER

Test number	1	2	3	4	5
Number of samples	24	24	18	24	18
Sample volume, ml	465	465	465	465	465
Ice mass, kg	2.59	2.31	2.35	2.08	2.16
Cooling water, kg	1.00	1.50	1.50	1.00	1.00

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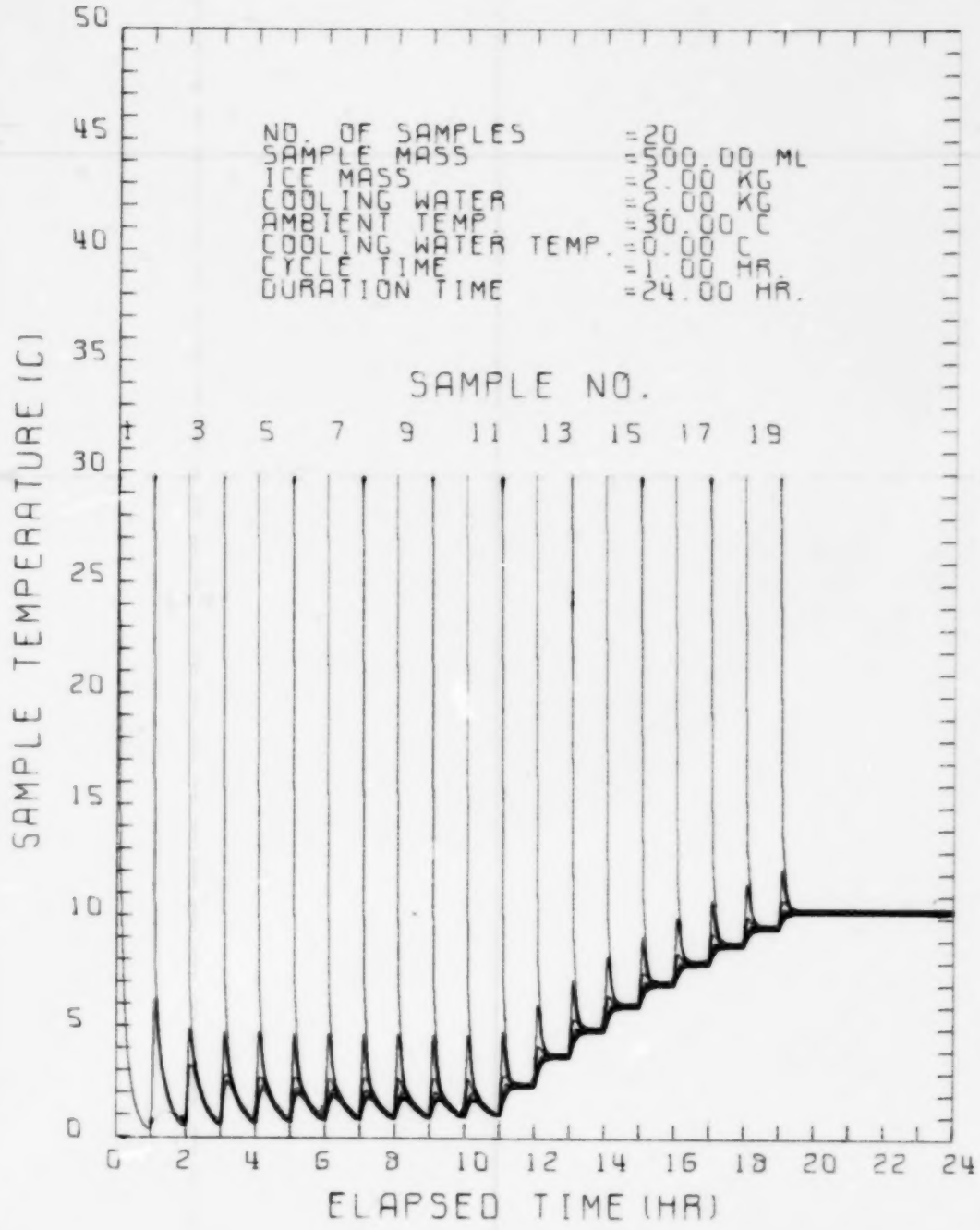
NO. OF SAMPLES =20
SAMPLE MASS =500.00 ML
ICE MASS =2.00 KG
COOLING WATER =2.00 KG
AMBIENT TEMP. =30.00 C
COOLING WATER TEMP. =0.00 C
CYCLE TIME =1.00 HR.
DURATION TIME =24.00 HR.
SAMPLE NO.
3 5 7 9 11 13 15 17 19
SAMPLE TEMPERATURE (C)
0 5 10 15 20 25 30 35 40 45 50
0 2 4 6 8 10 12 14 16 18 20 22 24
ELAPSED TIME (HR)

Figure 5. Calculated approach to equilibrium of an idealized, adiabatic sampler.

TABLE 1 (continued). TESTING DATA ON MANNING SAMPLER

Test number	1	2	3	4	5
Ambient temp., ^{o}C	30.00	30.00	23.50	28.40	33.00
Initial sample temp., ^{o}C	30.00	30.00	23.50	28.40	33.00
Cooling water temp., ^{o}C	22.70	23.00	22.40	21.50	22.70
Cycle time, hr	0.50	1.00	1.00	1.00	1.00
Duration time, hr	12.00	24.00	18.00	24.00	18.00
Bottle height, cm	12.70	12.70	12.70	12.70	12.70
Bottle thickness, mm	1.25	1.25	1.25	1.25	1.25
Thickness of sampler wall, cm	1.27	1.27	1.27	1.27	1.27
Thermal conductivity of bottle, cal/hr-cm-^{o}C	3.72	3.72	3.72	3.72	3.72
Thermal conductivity of sampler wall, cal/hr-cm-^{o}C	2.23	2.23	2.23	2.23	2.23

Test 1

In this test, crushed ice was stored in the ice compartment and cooling water was poured over the ice to increase the contact area between the water coolant and bottles. Results obtained from the test and the computer program are shown in Figure 6.

The experimental measurements in dashed lines indicate that a minimum temperature of 11.5^{o}C was reached at an elapsed time of 4 to 5 hours. The final measured temperature of samples approached 25^{o}C after 12 hours. This indicates that the cooling capacity in the sampler was inadequate and that the heat gain from the surroundings was extremely high for 12 hours. About 217 kcal (860 Btu) from outside the sampler were absorbed by the coolant and 55 kcal (220 Btu) were from the samples to the coolant.

Comparison of results from the test and the model shows that the temperature-time histories for each corresponding sample are nearly in phase; that a maximum temperature difference of 3^{o}C is observed; and that the difference at the lowest temperature for the first sample is about 0^{o}C.

Test 2

Test 2 is similar to Test 1 with the exception that the sampling cycle time and the duration time were 1 hour and 24 hours, respectively. Results are plotted in Figure 7 for both the theoretical calculation and the test.

A minimum temperature (first sample) of about 11.5^{o}C in the test was reached at an elapsed time of 4 to 5 hours which was similar to that in Test 1. The final measured temperature of samples after 24 hours was in the vicinity of 29^{o}C which was only 1^{o}C below the ambient temperature. Theoretically, the equilibrium temperature for all samples should be 12.41^{o}C

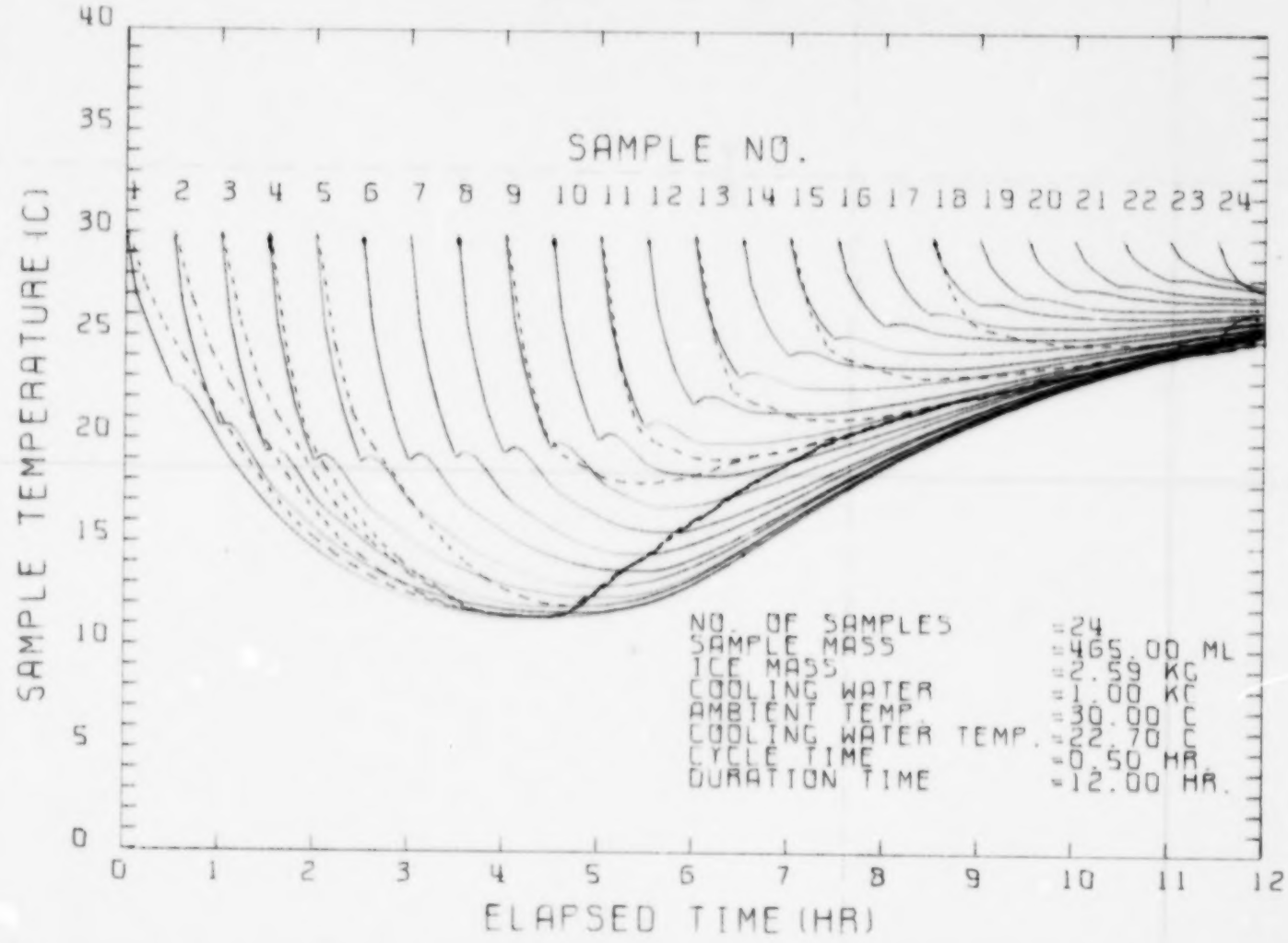
SAMPLE NO.
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SAMPLE TEMPERATURE (C)
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12
ELAPSED TIME (HR)
NO. OF SAMPLES = 24
SAMPLE MASS = 465.00 ML
ICE MASS = 2.59 KG
COOLING WATER = 1.00 KG
AMBIENT TEMP. = 30.00 C
COOLING WATER TEMP. = 2.70 C
CYCLE TIME = 0.50 HR.
DURATION TIME = 12.00 HR.

Figure 6. Comparison of results between mathematical model and Test No. 1.

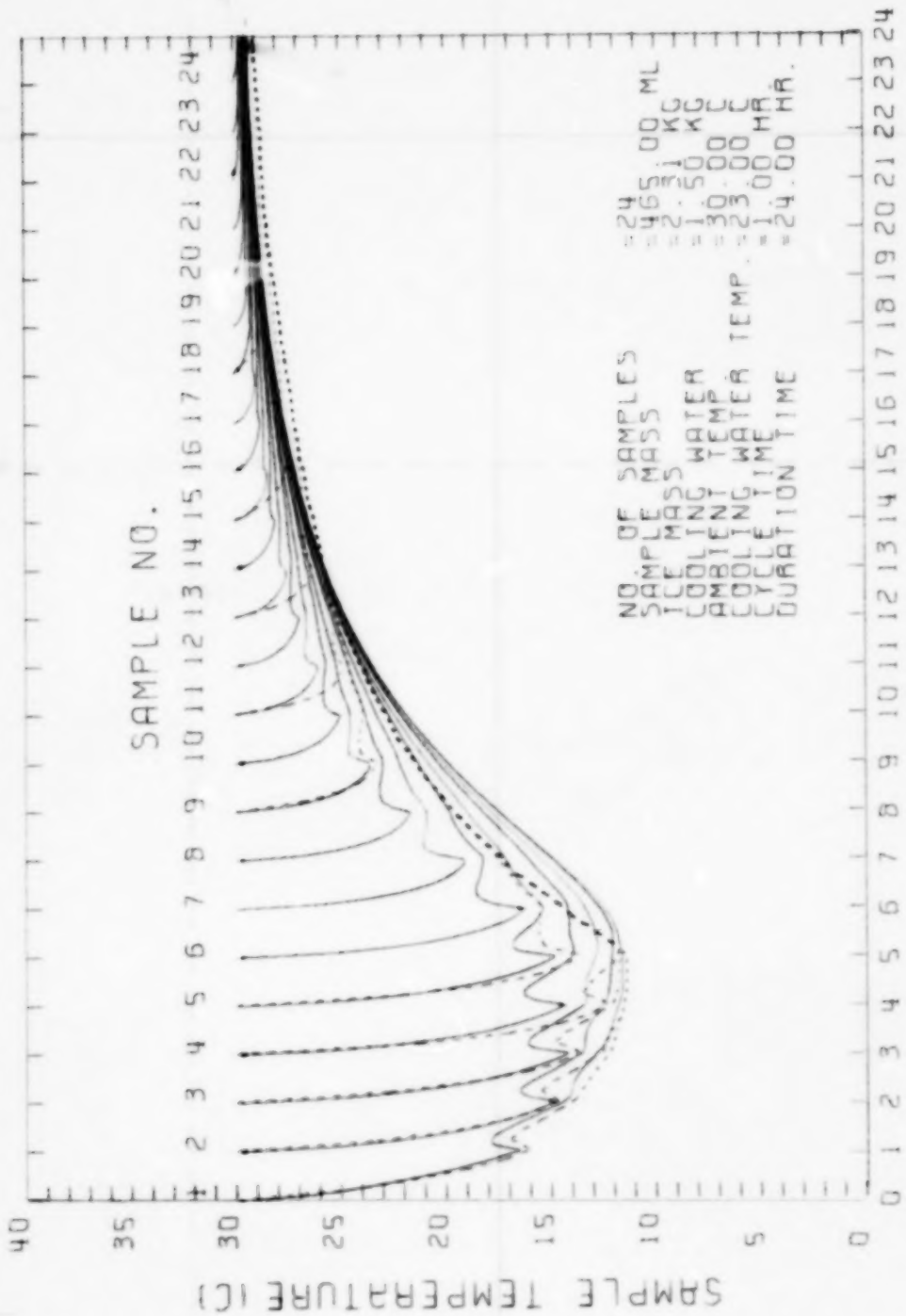
SAMPLE TEMPERATURE (C)
ELAPSED TIME (HR)
SAMPLE NO.
NO. OF SAMPLES = 24
SAMPLE MASS = 465.00 ML
ICE MASS = 2.361 KG
COOLING WATER AMBIENT TEMP = 30.000 C
COOLING WATER CYCLE TIME = 1.000 HR.
DURATION TIME = 24.00 HR.

Figure 7. Comparison of results between mathematical model and Test No. 2.

for a perfectly insulated sampler. Hence, this illustrates a need for the improvement of the sampler insulation. In this test, about 248 kcal (983 Btu) of heat were absorbed by the coolant from the surroundings and 11 kcal (44 Btu) were transferred from the samples for a 24-hour period.

A similar sample cooling rate as that in Test 1 was also observed. However, a sharp increase in temperature for sample i was obtained while sample i+1 was being taken. This is due to a larger temperature difference between samples i and i+1 for a longer cycle time (1 hour).

Comparison between the test and the model indicates that similar temperature-time histories for each corresponding sample as in Test 1 are observed. The maximum temperature difference is about 2°C.

Test 3

In this test, the number of samples taken was 18 and the ambient temperature was 23.5°C. Other parameters were similar to those in Test 2. Results for both the model and the test are plotted in Figure 8.

It took about 6 hours for the first sample to reach its lowest temperature of about 10°C and 18 hours to the final temperature of 21°C which was about 14°C higher than that in a perfectly insulated sampler. A calculation indicated that 205 kcal (815 Btu) and 28 kcal (110 Btu) were transferred from the surroundings and the sample to the coolant, respectively, for 18 hours. This indicated that the insulation was poor and that the cooling capacity was insufficient.

The theoretical calculation shows that the minimum temperature occurs at about 5 hours and the final temperature of the first sample is 1°C different from the test result. The maximum temperature difference observed from both results is about 2°C.

Test 4

Figure 9 shows results from Test 4 and the corresponding calculation for an ambient temperature of 28.4°C. Significant differences for samples 1, 2, and 3 between their respective results are observed. It was found that the three thermocouples were not centrally positioned. Other measured results are very comparable to those of the calculation. Except for samples 1, 2, and 3, the maximum temperature difference was less than 2°C.

The final temperature of samples in the test was close to 28°C which was only 0.5°C below the ambient temperature. Ideally, the final temperature would be 12.16°C for a perfectly insulated sampler. This indicates that the sampler was not properly insulated. The sampler cooling rate was also slow, requiring about 5 to 6 hours for the first sample to reach its minimum of 13°C.

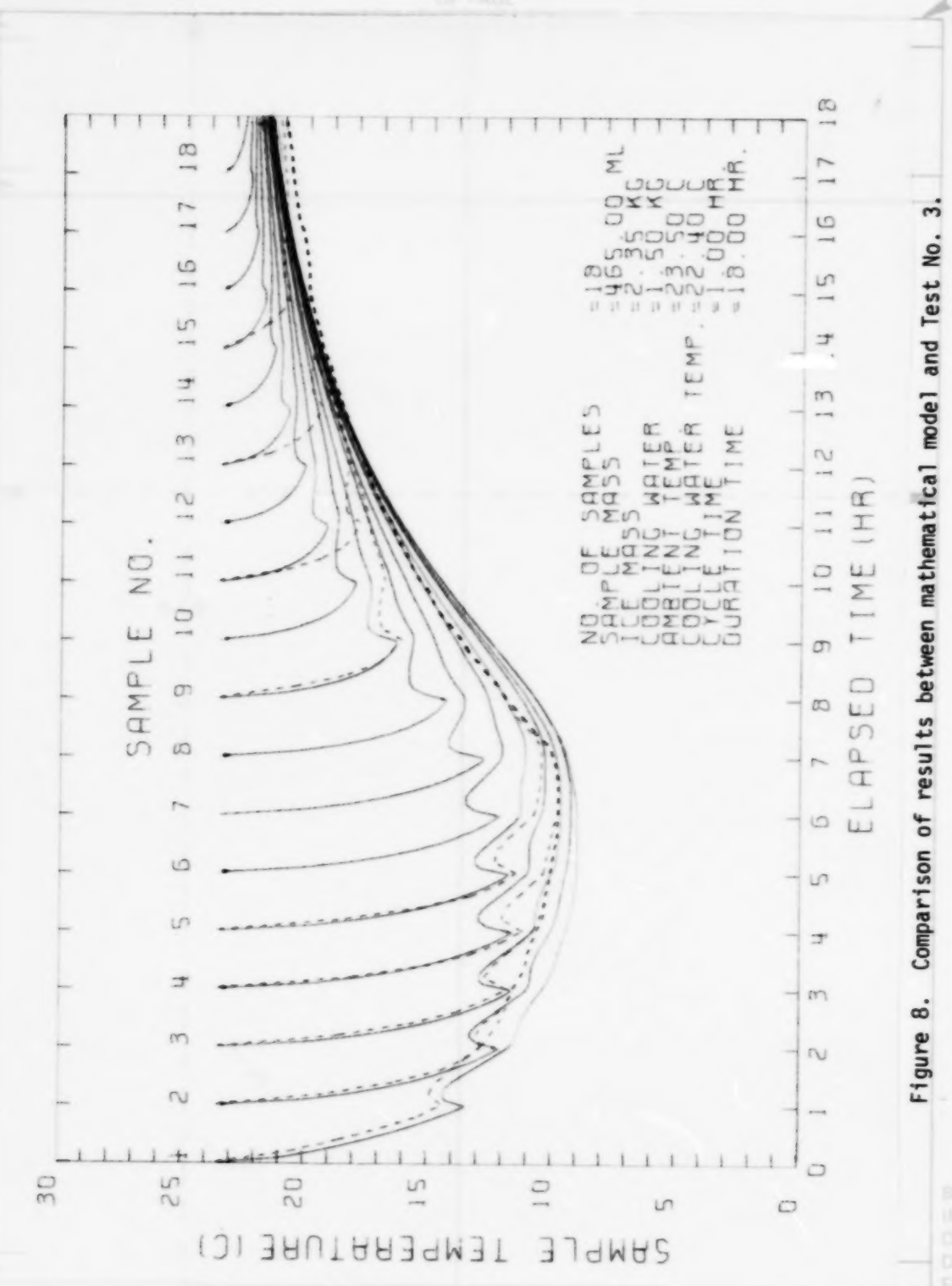

Figure 8. Comparison of results between mathematical model and Test No. 3.

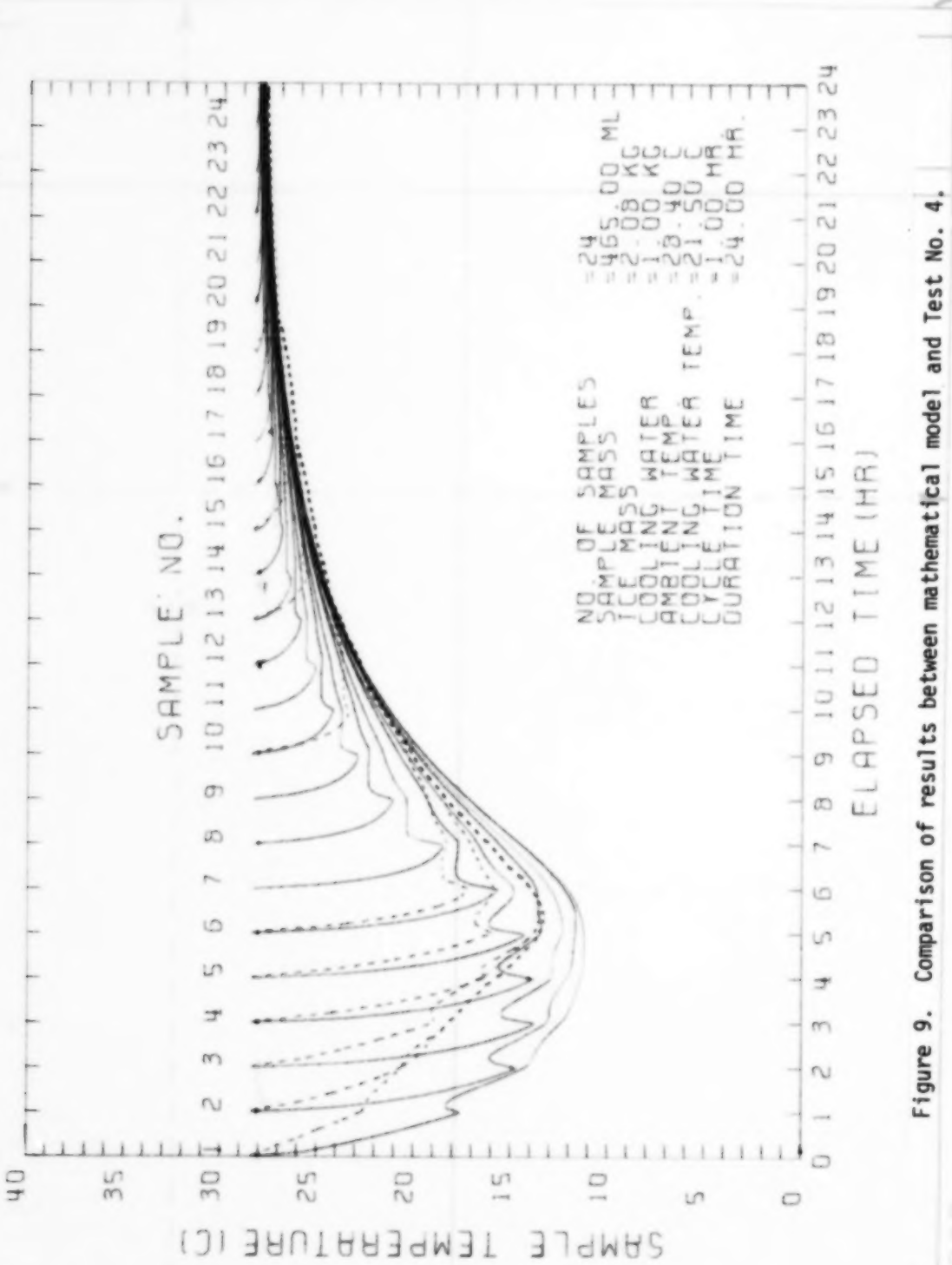
SAMPLE TEMPERATURE (C)
0
5
10
15
20
25
30
35
40
ELAPSED TIME (HR)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SAMPLE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
NO. OF SAMPLES 24
SAMPLES MASS 465.00 ML
TOOLING MASS 42.08 KG
AMBIENT TEMP 23.00 C
COOLING WATER TEMP 21.40 C
CYCLE TIME 1.00 HR
DURATION TIME 24.00 HR

Figure 9. Comparison of results between mathematical model and Test No. 4.

Test 5

Figure 10 displays results from Test 5 and the corresponding calculation for an ambient temperature of 33°C. Significant temperature differences for samples 1 and 2 between the test and the calculation are shown in the plot. A similar case as in Test 4 was found in this test. Other temperature readings are in good agreement.

The final measured temperature of samples after 18 hours was about 31.9°C and the minimum temperature (sample 1) was 15°C which occurred at about 5 hours. A perfectly insulated sampler would have an equilibrium temperature of 15.32°C.

The overall testing results indicate that the cooling process of a sample in the S-4000 sampler is slow. It takes about 4 to 6 hours for a sample to reach its minimum temperature. Furthermore, the sampler cooling capacity is inadequate and the sampler is not properly insulated. It is concluded that sample preservation by icing in this sampler is impossible under normal operating conditions.

Comparisons of results between the tests and the calculations indicate that both results show a similar trend of sample cooling process for all samples. Accuracy of the model, in general, is within 3°C.

MODIFICATION OF SAMPLER COOLING SYSTEM

Based on the mathematical model, the author proposes a design modification as shown in Figure 11. Three calculations under various conditions were conducted for this new design.

Figure 12 shows results obtained from the computer program with a K value of 0.45 cal/hr-cm-°C (0.03 Btu/hr-ft-°C), a sampler wall of 5.08 cm (2 in.), a contact area of 71 cm^2 (0.0764 ft^2) instead of the original 32 cm^2 (0.0347 ft^2) between the bottle and the coolant, a bottle height of 12.7 cm (6 in.), a bottle thickness of 1.25 mm, and an ice mass of 12 kg under an average temperature of 35°C for both the surroundings and the initial sample. It appears that the coolant capacity is slightly inadequate under these conditions for 24 hours. The final temperature of the first sample after 24 hours is 5.3°C. Furthermore, it takes about 5 hours for the first sample to reach 4°C.

Figure 13 shows results similar to those in Figure 12 except the ice is increased to 14 kg. The sample cooling rate is not improved. However, the final temperature of the first sample is about 4°C. Hence, the contact area between the bottle and the coolant needs to be increased.

Figure 14 shows results similar to those in Figure 13 except the contact area is assumed to be 130 cm^2 (0.14 ft^2). The sample cooling rate is greatly improved. It takes about 3 hours for the sample to reach 4°C. The final temperature of the first sample is similar to that in Figure 13, i.e., 4°C.

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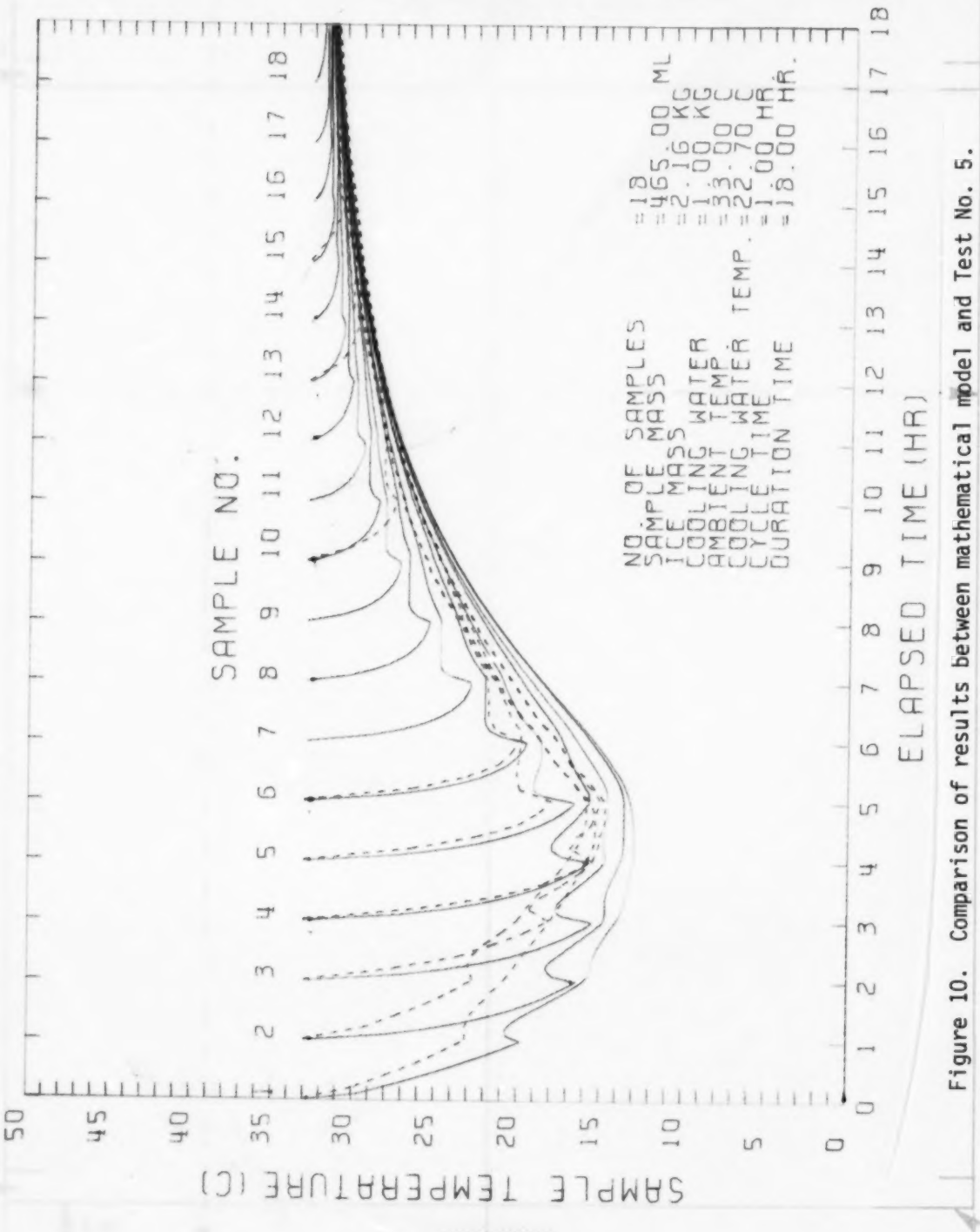
It is therefore possible to design a new sampler cooling system based on the revised model for sample preservation by icing under the above conditions.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SAMPLE MASS =465.00 ML
ICE MASS =2.160 KG
COOLING WATER TEMP. =1.000 KG
AMBIENT TEMP. =33.000 C
COOLING WATER TEMP. =22.70 C
CYCLE TIME =1.00 HR.
DURATION TIME =18.00 HR.
SAMPLE NO.
ELAPSED TIME (HR)
SAMPLE TEMPERATURE (C)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
50 45 40 35 30 25 20 15 10 5 0

Figure 10. Comparison of results between mathematical model and Test No. 5.

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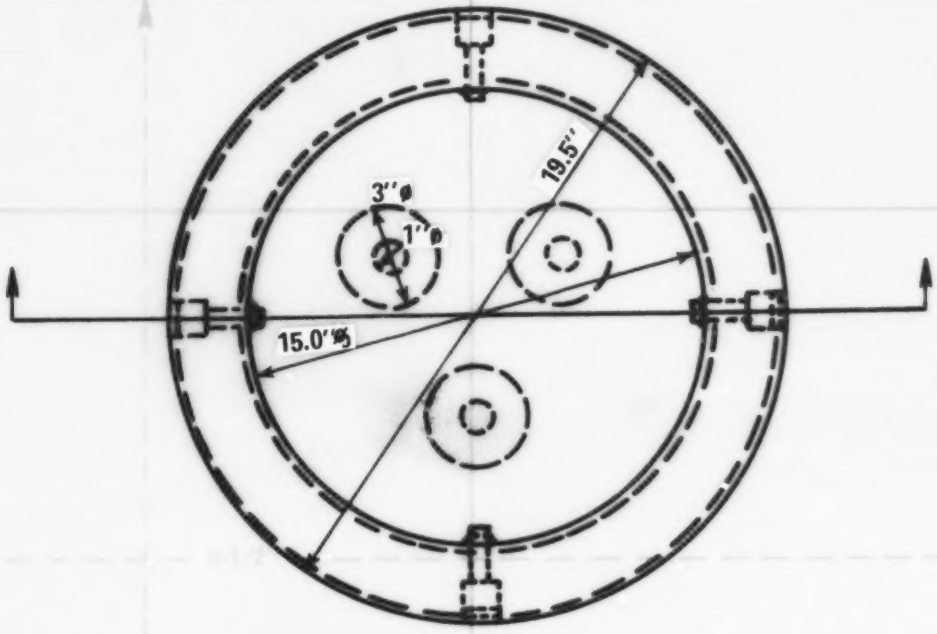

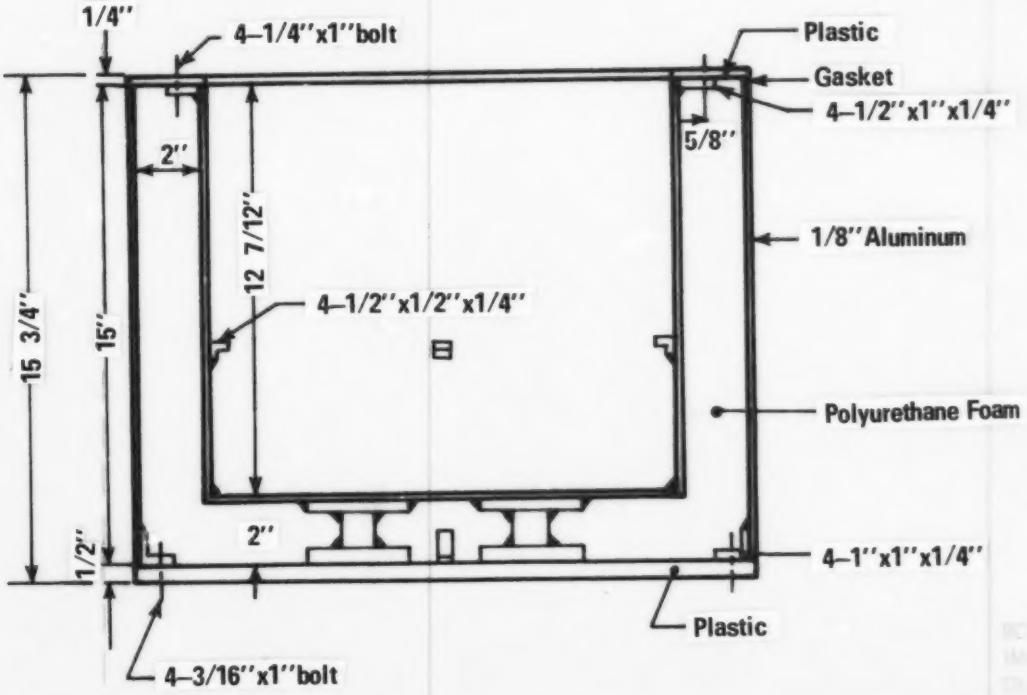

Figure 11. Modified design of sampler container.

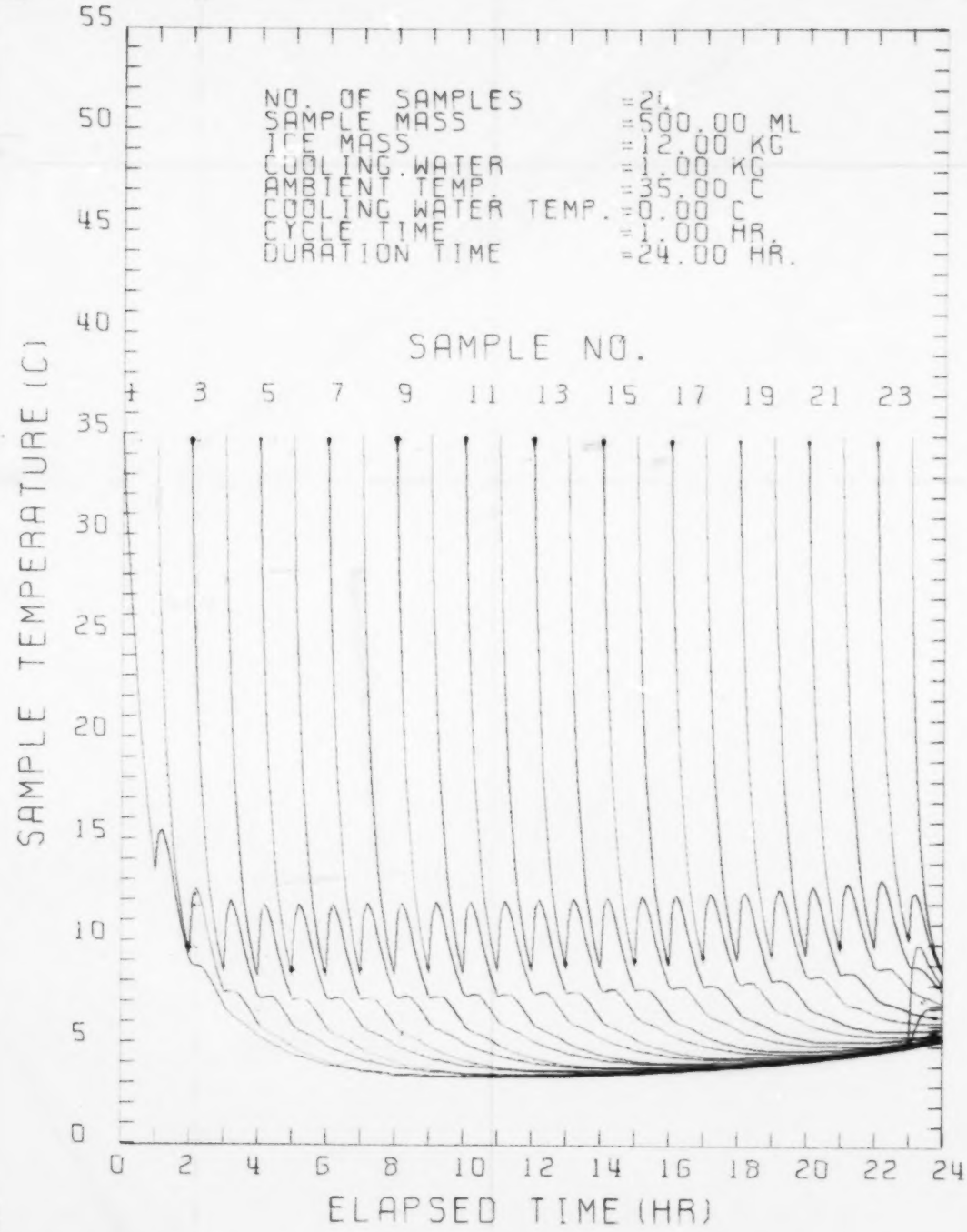
NO. OF SAMPLES =21
SAMPLE MASS =500.00 ML
ICE MASS =12.00 KG
COOLING WATER =1.00 KG
AMBIENT TEMP. =35.00 C
COOLING WATER TEMP. =0.00 C
CYCLE TIME =1.00 HR.
DURATION TIME =24.00 HR.
SAMPLE NO.
3 5 7 9 11 13 15 17 19 21 23
SAMPLE TEMPERATURE (C)
0 5 10 15 20 25 30 35 40 45 50 55
0 2 4 6 8 10 12 14 16 18 20 22 24
ELAPSED TIME (HR)

Figure 12. Theoretical calculation of modified sampler cooling system with a contact area of 71 cm^2 between bottle and coolant, and 12 kg of ice.

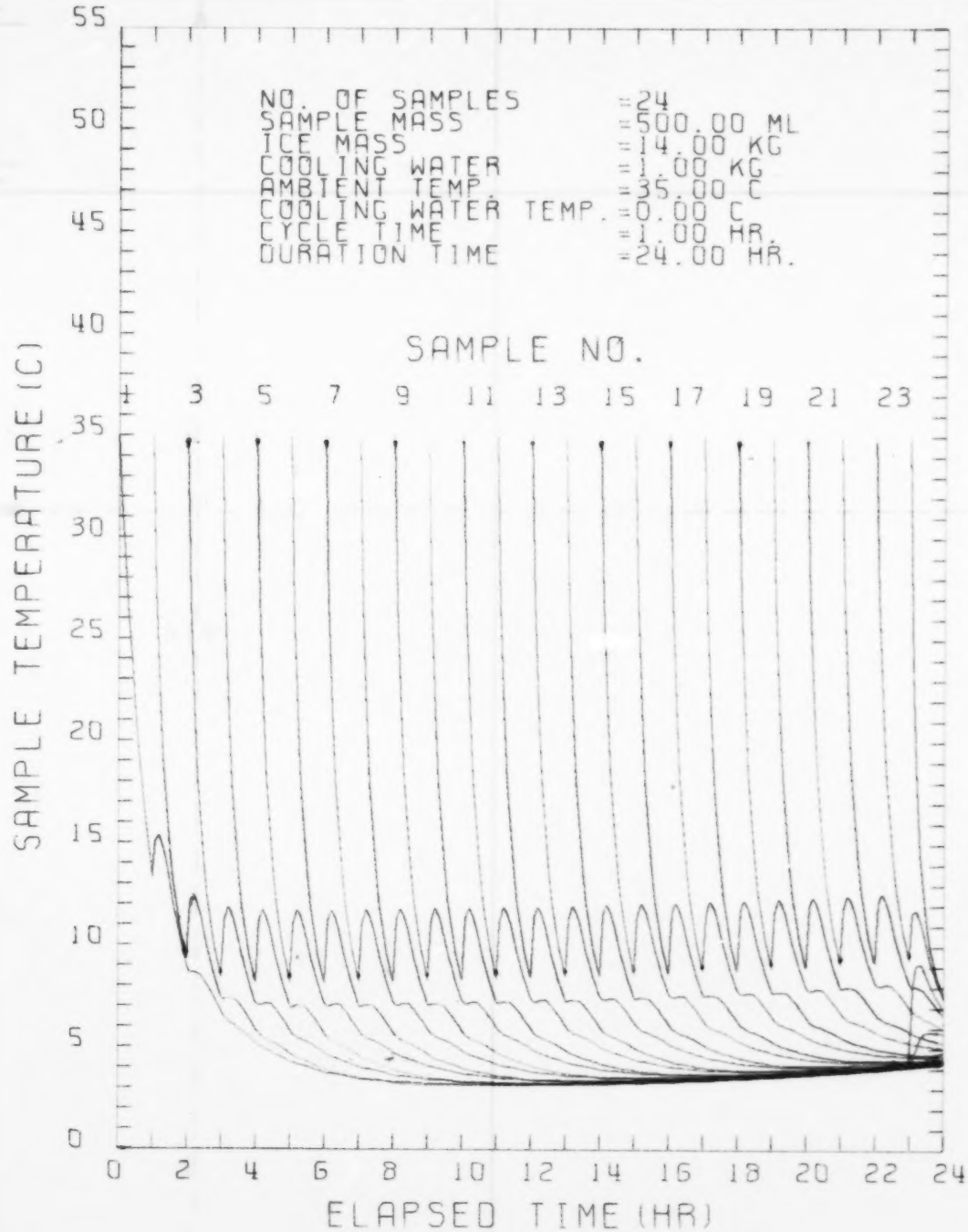
NO. OF SAMPLES =24
SAMPLE MASS =500.00 ML
ICE MASS =14.00 KG
COOLING WATER =1.00 KG
AMBIENT TEMP. =35.00 C
COOLING WATER TEMP. =0.00 C
CYCLE TIME =1.00 HR.
DURATION TIME =24.00 HR.
SAMPLE NO.
3 5 7 9 11 13 15 17 19 21 23
SAMPLE TEMPERATURE (C)
0 5 10 15 20 25 30 35 40 45 50 55
0 2 4 6 8 10 12 14 16 18 20 22 24
ELAPSED TIME (HR)

Figure 13. Theoretical calculation of modified sampler cooling system with a contact area of 71 cm^2 between bottle and coolant, and 14 kg of ice.

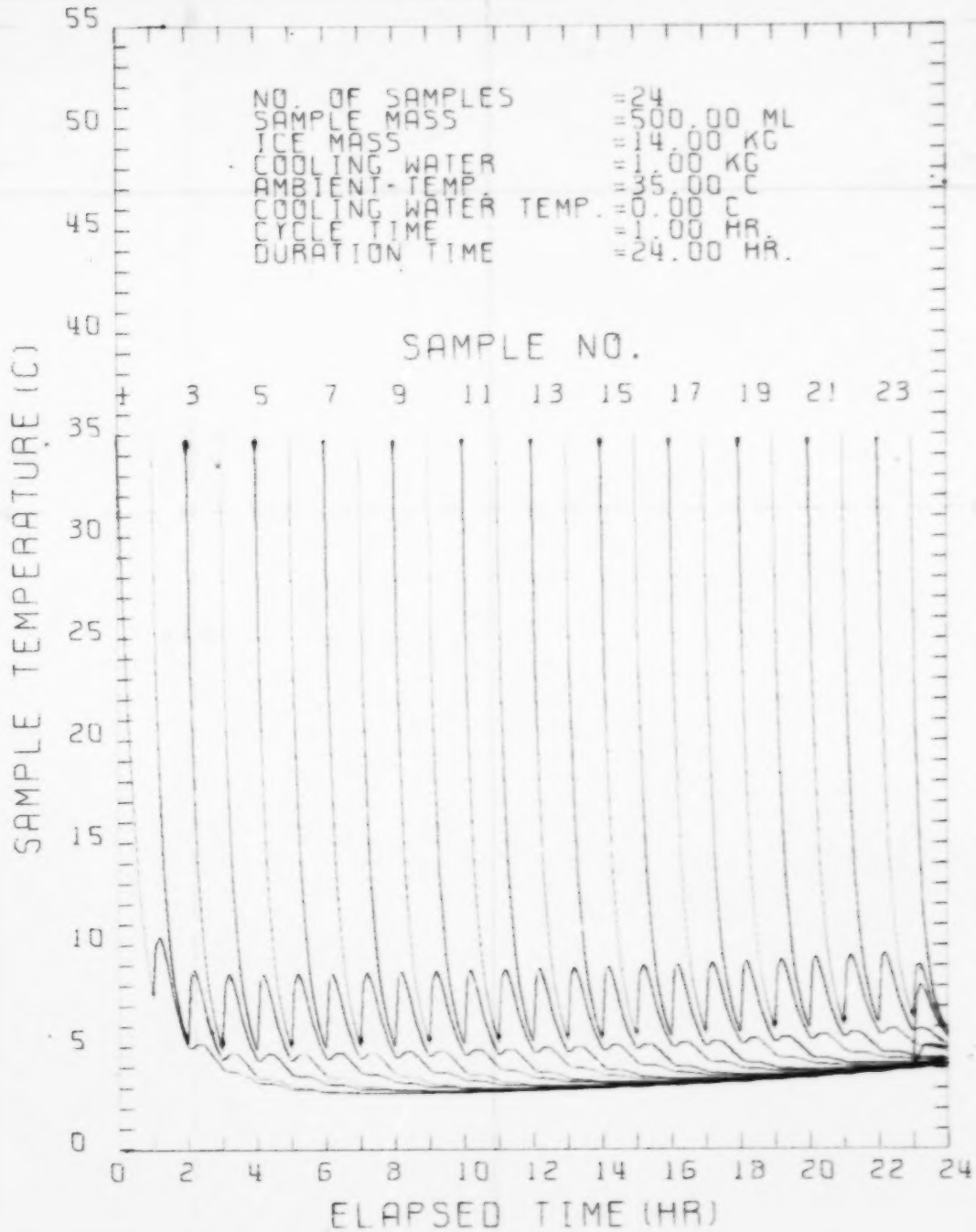
NO. OF SAMPLES =24
SAMPLE MASS =500.00 ML
ICE MASS =14.00 KG
COOLING WATER =1.00 KG
AMBIENT-TEMP =35.00 C
COOLING WATER TEMP. =0.00 C
CYCLE TIME =1.00 HR.
DURATION TIME =24.00 HR.
SAMPLE NO.
3 5 7 9 11 13 15 17 19 21 23
SAMPLE TEMPERATURE (C)
0 5 10 15 20 25 30 35 40 45 50 55
0 2 4 6 8 10 12 14 16 18 20 22 24
ELAPSED TIME (HR)

Figure 14. Theoretical calculation of modified sampler cooling system with a contact area of 130 cm^2 between bottle and coolant, and 14 kg of ice.

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